RELIABAILITY ASSESMENT OF SOUTHERN CROATIAN TRANSMISSION NETWORK

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Abstract

This paper presents the reliability assessment of the southern part of Croatian transmission network in the region around the Dubrovnik city. Reliability of the southern part is very low in present time, and several hard power supply interruptions have appeared in years 2009 and 2010. There are plans of installing a new GIS (Gas Isolated Switchgear) substation 220/110 kV Plat in that region. Reliability assessment was performed, and reliability indices were computed before and after construction of a new GIS substation 220/110 kV Plat. The reliability is analyzed using *DIgSILENT Power Factory 14.0* software. Input data were obtained from annual reports of HEP TSO (Croatian Electric Utility Transmission System Operator) and statistic analysis of data was performed first. Since there are no statistical data for new GIS substations, input data for them were taken from the relevant literature. In reliability assessment Markov state space model of primary substation components such as busbars, transformers, breakers and disconectors was used. Load is modeled at the output substation busbars with maximum active and reactive power. The state enumeration method is used for reliability analysis. Results are showing high level of improving reliability after a new GIS 220/110 kV substation is put in the function.

Keywords: Reliability, transmission network, reliability indices, GIS substation

Presenting Author's biography

Krešimir Fekete BSc. (b. 1983). He obtained his BSc degree in 2006 in the field of Electrical Power Engineering from the Faculty of Electrical Engineering, J.J. Strossmayer University of Osijek, Croatia. Currently, he works in the Power System Department within the Faculty of Electrical Engineering, University of Osijek. His topics of research include electricity markets modeling and simulation, energy markets integration and power system analysis and control.

1 Introduction

The electrical power system provides the production and delivery of electrical energy in sufficient quantities to areas that need electricity through a grid. The goal of electrical power system is secure and reliable electricity supply of costumers at minimum costs. Due to the complexity of power system, its stochastic nature and its extremely large number of component, performing an adequacy assessment and analyzing the system performance for a practical system, is a very sophisticated work and requires a long computational time. Such analyses include many aspects such as load flow analysis, contingency assessment, generation rescheduling, transmission overload alleviation, load curtailment etc. The analytical approach is one of the most common methods applied for reliability assessment of power systems. Results obtained from applying this approach provide an appropriate benchmark for evaluating the system performance and its reliability. Reliability is the probability of a device or system to perform its function adequately, for the period of time intended, under the operating conditions intended [1]. In this paper, the reliability assessment of the southern part of Croatian transmission network in the region around the Dubrovnik city is performed in *DIgSILENT Power Factory 14.0* software. Motivation for this analysis is planned construction of new 220/x kV GIS substation in that region. The reliability indices were computed for two cases: before and after construction of a new GIS substation 220/110 kV.

2 Mathematical model of components

2.1 Markov model of renewable components with two different states

Power system elements (transformers, lines, cables, busbars, etc.) are renewable components. Regarding to reliability of supply, they can have two different states – they are either available (ready to operate) or unavailable, i.e. blocked [2]. Two states component model is the model most often used, since it gives the best description of the continuous operation of a component. It is presented in Figure 1.

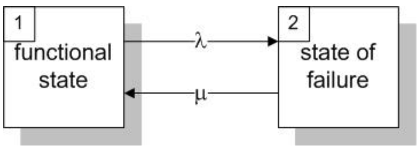

Fig. 1 Model of a component with two states (renewable)

Symbols:

1 - functional component
2 - blocked component;
λ - component failure intensity;
μ - component repair intensity.

Probability of being in a state 1 and 2 is:

$$P_1 = \frac{\mu}{\lambda + \mu}, \quad P_2 = \frac{\lambda}{\lambda + \mu} \tag{1}$$

Frequency of being in a state 1 and 2 is :

$$f_1 = \lambda \cdot P_1 = \frac{\lambda\mu}{\lambda + \mu}, \quad f_2 = \mu \cdot P_2 = \frac{\lambda\mu}{\lambda + \mu} \tag{2}$$

2.2 Model of a system with two components (for a coincidence of transformer and busbar failure)

The model presented in Figure 2 shows the state of two different components - each component can be either ready to operate (i.e. functional), or not ready to operate (blocked).

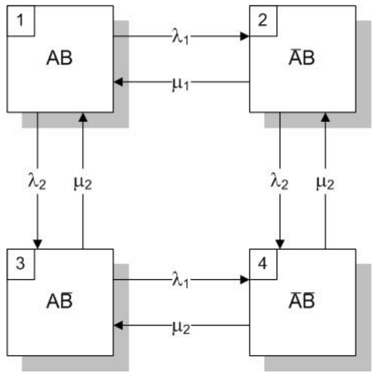

Fig. 2 Model of two component with two states

Symbols:

A - first component ; B – second component;
1 – components A and B in a functional state;
2 – component A faulty, and B functional;
3 – component A functional, and B faulty;
4 - components A and B faulty;

λ_1 and μ_1- failure and repair intensity of component A;
λ_2 and μ_2 -failure and repair intensity of component B;

This model is applied during analysis of switchgear failures for transformer and busbar failure coincidence. The basic premise of all considerations is that the possibility of two or more events taking place simultaneously is ruled out, as a result of which the possibilities of direct transitions between states 1 and 4, i.e. 2 and 3 within the model are ruled out.

Stationary system solutions, i.e. stationary probabilities of states are:

$$\begin{aligned} P_1 &= \frac{\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \quad P_2 = \frac{\lambda_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \\ P_3 &= \frac{\mu_1\lambda_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \quad P_4 = \frac{\lambda_1\lambda_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \end{aligned} \tag{3}$$

Since that expressions: $A = \frac{\mu}{\lambda + \mu}; \quad N = \frac{\lambda}{\lambda + \mu}$

present stationary availability, that is, unavailability of one component, the stationary probabilities of states in the case of two components system can be expressed as follows:

$$P_1 = A_1A_2; \; P_2 = N_1A_2; \; P_3 = A_1N_2; \; P_4 = N_1N_2 \tag{4}$$

According to the model of a system with two different components, the frequency of an individual state can be determined either as a product of the state probability and the sum of intensity of abandoning that identical state, or as a product of the sum of intensity of entering the state and the probability of a state that is being abandoned. Frequencies are equal, whether they are observed from a perspective of exits, or from a perspective of entrances. According to that, frequencies of states are:

$$\begin{aligned} f_1 &= P_1(\lambda_1+\lambda_2) = A_1A_2(\lambda_1+\lambda_2) = f_1A_2 + f_2A_1 \\ f_2 &= P_2(\mu_1+\lambda_2) = N_1A_2(\mu_1+\lambda_2) = f_1A_2 + f_2N_1 \\ f_3 &= P_3(\lambda_1+\mu_2) = A_1N_2(\lambda_1+\mu_2) = f_1N_2 + f_2A_1 \\ f_4 &= P_4(\mu_1+\mu_2) = N_1N_2(\mu_1+\mu_2) = f_1N_2 + f_2N_1 \end{aligned} \tag{5}$$

2.3 Model of component with maintenance (planned repair)

Switchgear components are renewable components and their maintenance (planned repair) is carried out periodically. Maintenance of switchgear components increases their reliability and availability, because the tendency of growth of failure intensity function is being reduced and maintained at a sufficiently low constant value. Figure 3 shows the Markov model of component with maintenance. It is supposed that the planned repair of a component will not be performed when a component is not functional, and upon finishing the repair, a component is again ready for operation (available).

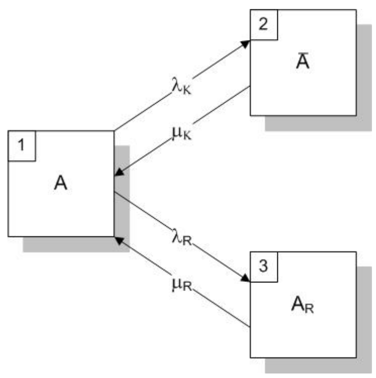

Fig. 3 Model of component with maintenance

Symbols:

1- component in operation;
2- component A blocked;
3- component A under repair;

λ_R and μ_R- intensity of repair and repair completion of component A;

λ_K and μ_K - intensity of malfunction and repair of component A;

Stationary system solutions, i.e. stationary probabilities of states are:

$$P_1 = \frac{\mu_K\mu_R}{\mu_K\mu_R+\lambda_K\mu_R+\lambda_R\mu_K}, P_2 = \frac{\lambda_K\mu_R}{\mu_K\mu_R+\lambda_K\mu_R+\lambda_R\mu_K}, \quad P_3 = \frac{\lambda_R\mu_K}{\mu_K\mu_R+\lambda_K\mu_R+\lambda_R\mu_K} \tag{6}$$

Based on earlier considerations, it follows that state „1“ denotes component availability, state “2” denotes a failure-induced component unavailability, and state “3” – component unavailability due to repair:

$$P_1 = A; \; P_2 = N_K; \; P_3 = N_R \tag{7}$$

Frequencies of failure and repair states are:

$$\begin{aligned} f_2 &= P_1\cdot\lambda_K = P_2\cdot\mu_K = \frac{\lambda_K\mu_K\mu_R}{\mu_K\mu_R+\lambda_K\mu_R+\lambda_R\mu_K} \\ f_3 &= P_1\cdot\lambda_R = P_3\cdot\mu_r = \frac{\lambda_R\mu_R\mu_K}{\mu_K\mu_R+\lambda_K\mu_R+\lambda_R\mu_K} \end{aligned} \tag{8}$$

Correlation of planned repair and intensity of malfunction is presented on Figure 4. Maintenance and repairing of component is carried out periodically in intervals T which results with increasing of reliability.

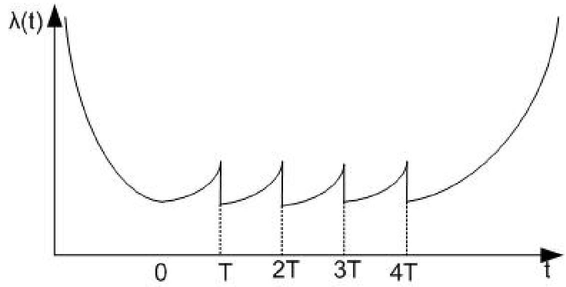

Fig. 4 Impact of periodical planned maintenance of component on its intensity of malfunction

2.4 Failure coincidence model with planned maintenance – repair

Preventive maintenance and repairs are conducted in order to keep the frequency of component failures at the lowest possible level. However, when these coincide with failures of other components in the system, the number of system failures may be increased. Thus, if possible, preventive maintenance and repairs should be conducted when they would not have negative effects on the system in general. Usually the frequency and the mean time of planned maintenance or repair are considered to be previously scheduled. The procedure of planned maintenance and repair of the component is not initiated if the removal of that component from the system would cause system failure due to already existing failures or previously initiated planned maintenance and repair. The possibility of withholding it in operation is due to the fact that it is a planned procedure which is possible to conduct at an earlier time or postpone it until the time is right. Also, it is generally considered that once the repair has been initiated, it has to be finished.

Figure 5 shows a case of failure coincidence with planned maintenance and repair. If the possibility of transition from state “3” into state “4” is removed, then the request that the repair cannot be initiated in state “3” is accepted, i.e. during the failure state of the other component. However, if the state “4” does not represent system failure state, that transition is allowed and the failure and repair processes are independent.

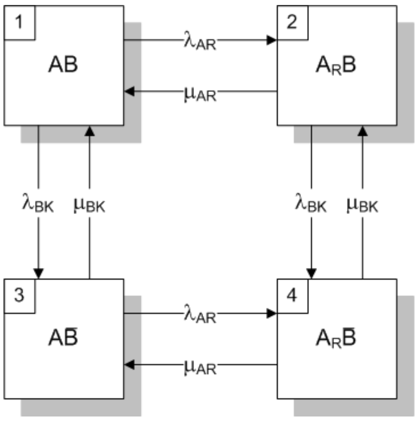

Fig. 5 Failure coincidence model of planned maintenance and repair with failure

Symbols:

A- first component ; B – second component;

1- components A and B in operation;
2- component A in repair, and B in operation;
3- component A in operation, and B in failure;
4- component A in repair, and B in failure;

λA_R - component A repair intensity;
μ_{AR} - component A repair intensity;
λ_{BK} - component B failure intensity;
μ_{BK} - component B repair intensity.
μ_p - component repair intensity;

The probabilities of being in certain states in case the transition from state “3” into state “4” is allowed, since state “4” does not represent system failure state, are as follows:

$$P_1=\frac{\mu_{AR}\mu_{BK}}{(\lambda_{AR}+\mu_{AR})(\lambda_{BK}+\mu_{BK})};\ P_2=\frac{\lambda_{AR}\mu_{BK}}{(\lambda_{AR}+\mu_{AR})(\lambda_{BK}+\mu_{BK})}$$
$$P_3=\frac{\lambda_{BK}\mu_{AR}}{(\lambda_{AR}+\mu_{AR})(\lambda_{BK}+\mu_{BK})};\ P_4=\frac{\lambda_{AR}\lambda_{BK}}{(\lambda_{AR}+\mu_{AR})(\lambda_{BK}+\mu_{BK})} \quad (9)$$

However, if state “4” also means system failure, the transition from state “3” into state “4” is not allowed, which means that the frequency of repair of the first component in the third and fourth system equation has a zero value ($\lambda^*_{AR}=0$). In that case, the values are:

$$P_1=\frac{\mu_{AR}\mu_{BK}(\lambda_{BK}+\mu_{AR}+\mu_{BK})}{(\lambda_{BK}+\mu_{BK})[\mu_{AR}(\lambda_{AR}+\lambda_{BK}+\mu_{AR}+\mu_{BK})+\lambda_{AR}\mu_{BK}]}$$
$$P_2=\frac{\lambda_{AR}\mu_{BK}(\mu_{AR}+\mu_{BK})}{(\lambda_{BK}+\mu_{BK})[\mu_{AR}(\lambda_{AR}+\lambda_{BK}+\mu_{AR}+\mu_{BK})+\lambda_{AR}\mu_{BK}]}$$
$$P_3=\frac{\lambda_{BK}\mu_{AR}(\lambda_{AR}+\lambda_{BK}+\mu_{AR}+\mu_{BK})}{(\lambda_{BK}+\mu_{BK})[\mu_{AR}(\lambda_{AR}+\lambda_{BK}+\mu_{AR}+\mu_{BK})+\lambda_{AR}\mu_{BK}]} \quad (10)$$
$$P_4=\frac{\lambda_{AR}\lambda_{BK}\mu_{BK}}{(\lambda_{BK}+\mu_{BK})[\mu_{AR}(\lambda_{AR}+\lambda_{BK}+\mu_{AR}+\mu_{BK})+\lambda_{AR}\mu_{BK}]}$$

Since the most common frequencies of component repair and maintenance are significantly higher than the respective frequencies of entering into those states, i.e. the multiple products of very small values can be disregarded, the near solution values (10) are:

$$P_1\approx 1;\ P_2\approx\frac{\lambda_{AR}}{\mu_{AR}};\ P_3\approx\frac{\lambda_{BK}}{\mu_{BK}};$$
$$P_4\approx\frac{\lambda_{AR}\lambda_{BK}}{\mu_{AR}(\mu_{AR}+\mu_{BK})} \quad (11)$$

The frequency of system failure, (failure and repair coincidence state) which also means the failure of the system is:

$$f_4=P_4(\mu_{AR}+\mu_{BK})\approx\frac{\lambda_{AR}\lambda_{BK}}{\mu_{AR}(\mu_{AR}+\mu_{BK})}(\mu_{AR}+\mu_{BK})=\frac{\lambda_{AR}\lambda_{BK}}{\mu_{AR}} \quad (12)$$

The mean time of failure coincidence with planned maintenance and repair is:

$$T_k=\frac{P_4}{f_4}\approx\frac{1}{\mu_{AR}+\mu_{BK}} \quad (13)$$

3 Reliability indices calculation

In this paper *DIgSILENT Power Factory 14.0* software is used for calculation of reliability assessment. *DIgSILENT* applies system state enumeration method based on Markov model explained in previous chapters. The enumeration method is analytical approach where all relevant possible states of the system are analyzed one by one [3]. A fast "topological" state enumeration method is used which ensures that each possible system state is only analyzed once. Realistic state frequencies (average occurrences per year) are calculated by considering only the transitions from a healthy situation to an unhealthy one and back again. Calculation of power flow is performed using Newton-Raphson method. In reliability evaluations, calculation of load flows must be repeated for each state that is simulated in the process and several times if the system load changes are considered.

The network reliability assessment produces two sets of indices:

- Load point indices
- System indices

The expected values of supply interruption indices on consumer busbars (load point) are calculated in the following way:

Supply interruption probability

$$P_k = \sum_j P_j \cdot P_{kj} \tag{11}$$

Supply interruption frequency (1/year)

$$f_k = \sum_j f_j \cdot P_{kj} \tag{12}$$

Expected undelivered power due to interruption (MW/year)

$$\Delta L_k = \sum_j L_{kj} \cdot f_j \tag{13}$$

Expected undelivered energy (MWh/year)

$$\Delta W_k = \sum_j L_{kj} \cdot r_{kj} \cdot f = \sum_j L_{kj} \cdot P_{kj} \cdot 8760_j \tag{14}$$

Expected supply interruption duration (h/year)

$$r_k = \sum_j r_{kj} \cdot f_j = \sum_j P_{kj} \cdot 8760 \tag{15}$$

where: P_j - event probability "j"

P_{kj} - probability of consumption in point "k" being higher than the maximal power that can be supplied (determined by the power flows analysis, $P_{kj} = 0$ if consumption is not higher than the possible power that can be supplied, $P_{kj} = 1$ if it is)

f_j - event frequency "j"

L_{kj} - undelivered power at point "k" due to event "j"

r_{kj} - mean time of supply interruption duration at point "k" due to event "j".

System indices of the network reliability assessment are:

- **SAIFI -** System Average Interruption Frequency Index [1/C/a], is the mean interruption frequency found by dividing by the total number of customers in the analyzed system.
- **CAIFI -** Customer Average Interruption Frequency Index [1/A/a], is the mean interruption frequency found by dividing by the total amount of affected customers, i.e. customers that will suffer interruptions, in the analyzed system.
- **SAIDI -** System Average Interruption Duration Index [h/C/a], is the mean time per year that customers are interrupted, by dividing by the total number of customers in the analyzed system.
- **CAIDI -** Customer Average Interruption Duration Index [h], is the mean duration per interruption.
- **ASAI -** Average Service Availability Index is the probability of having one or more loads interrupted.
- **ASUI -** Average Service Unavailability Index is the probability of having all loads supplied.
- **ENS -** Energy Not Supplied [MWh/a], is the total amount of energy which is expected not to be delivered to the loads.
- **AENS -** Average Energy Not Supplied [MWh/C/a], is the average amount of energy not supplied, for all customers.

4 Southern Croatian transmission network

4.1 Transmission network before GIS substation installation

Main consumption in the southern part of Croatia is around of the city Dubrovnik. The consumers are feed through the one transformer station 110/x kV called TS Komolac. There are also two generators in hydro power plant (HPP) near Dubrovnik. One generator is connected to TS Komolac and other generator is connected to transformer station TS Trebinje in Bosnia and Herzegovina. Transmission network before GIS substation installation is shown in Fig. 6.

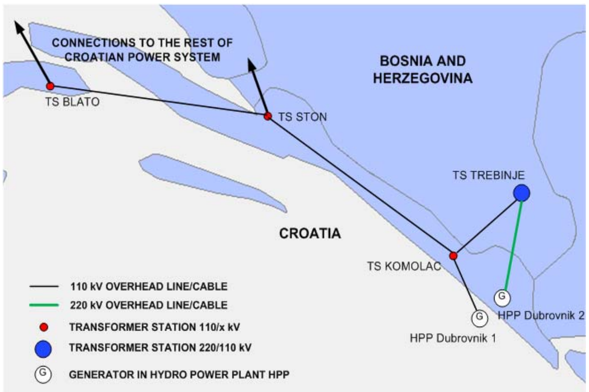

Fig. 6 Transmission network before GIS substation installation

4.2 Transmission network after GIS substation installation

New 220/110 kV GIS substation called TS Plat is planned to install between HPP and TS Komolac as shown in Fig. 7. After the construction of substation southern part of Croatia will get another feeding point (besides TS Komolac).

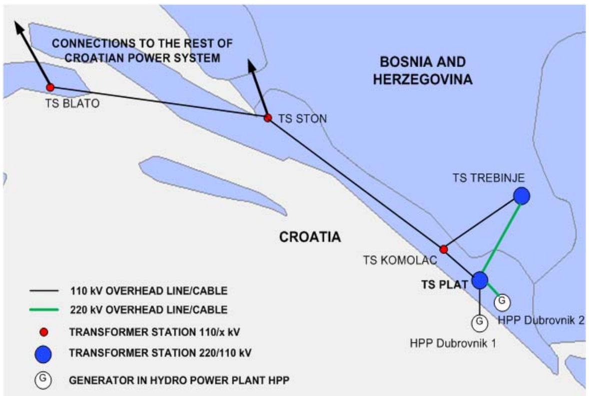

Fig. 7 Transmission network after GIS substation installation

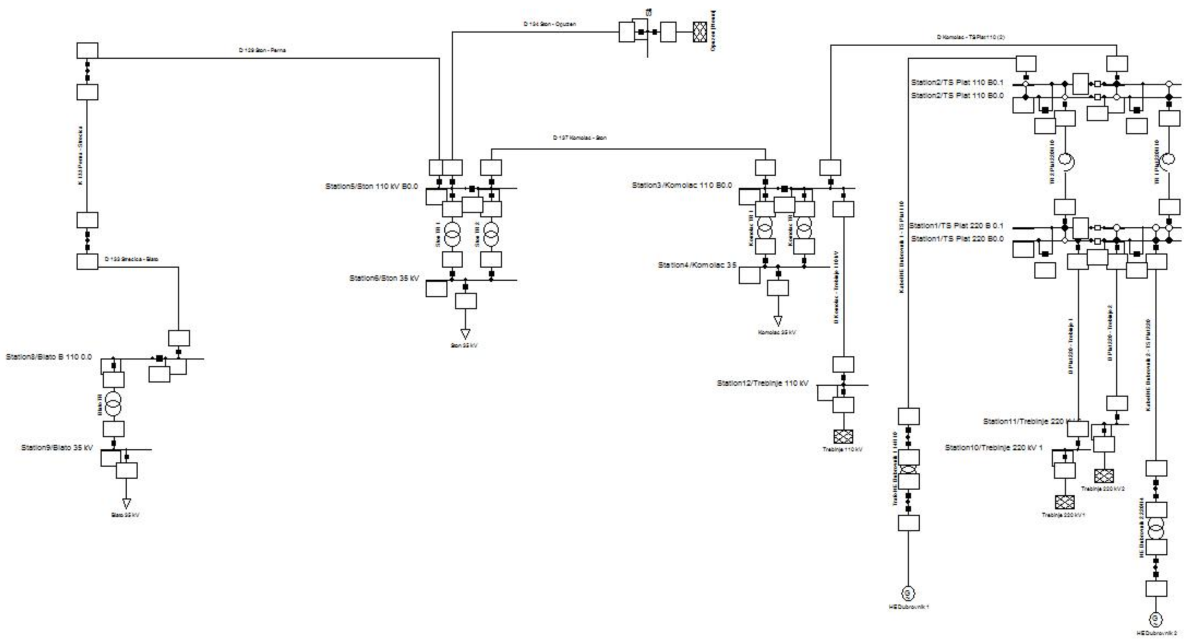

Fig. 8 Computer model of southern Croatian transmission network

4.3 Computer model of southern Croatian transmission network

DIgSILENT Power Factory 14.0 software is used to create a computer model of southern Croatian transmission network. Two models are created: one before installing new 220/110 kV substation and other after installing it. Computer model contains in detail modeled transmission network (220 kV and 110 kV) of southern Croatia with two generators in HPP and transformer stations 110/x kV and 220/x kV. Computer model is after GIS installation is given in Fig. 8. In reliability assessment Markov state space model of primary substation components such as busbars, transformers, breakers and disconectors was used. Transmission lines and generators are also modeled in reliability assessment. Load is modeled at the output substation busbars with maximum active and reactive power. All necessary data for reliability analysis are obtained from the available statistical publications of Croatian electric utility HEP [4]. Since there are no statistical data for new GIS substations, input data for them were taken from the relevant literature [5] and [6].

5 Simulation results

Simulation reliability indices explained in Chapter 3 are obtained for every case. Summary results can be seen in Tab.1.

As can be seen in Tab. 1, after installation of GIS substation reliability indices are improving significantly.

Tab. 1 Summary results of reliability analysis

Index	Before GIS installation	After GIS installation	Unit
CAIFI	6.2284	1.1933	1/A/a
SAIDI	8.0390	0.6360	1/C/a
CAIDI	1.2910	0.5300	h
ASAI	0.999082	0.999927	-
ASUI	0.000918	0.000073	-
ENS	325.5540	35.9850	MWh/a
AENS	108.5180	11.9950	MWh/C/a

For example, Fig. 9 shows comparison of CAIFI (Customer Average Interruption Frequency Index) before and after GIS installation. In the second case, CAIFI is five times less than in the first case.

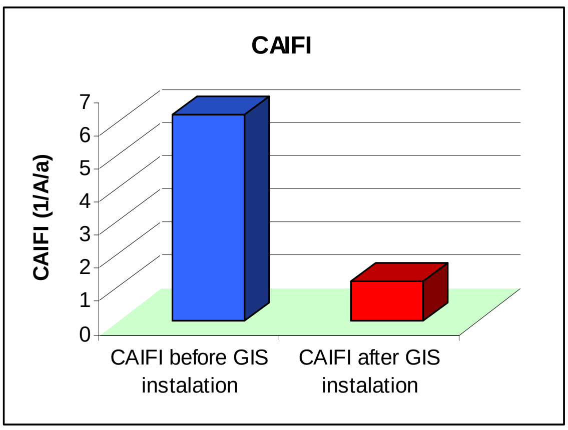

Fig. 9 CAIFI before and after GIS installation

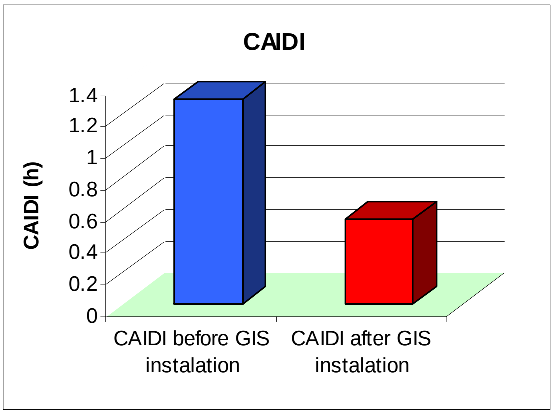

Fig. 10 CAIDI before and after GIS installation

Comparisons of CAIDI (Customer Average Interruption Duration Index) and ENS (Energy Not Supplied) before and after GIS installation are shown in Fig. 10 and Fig. 11.

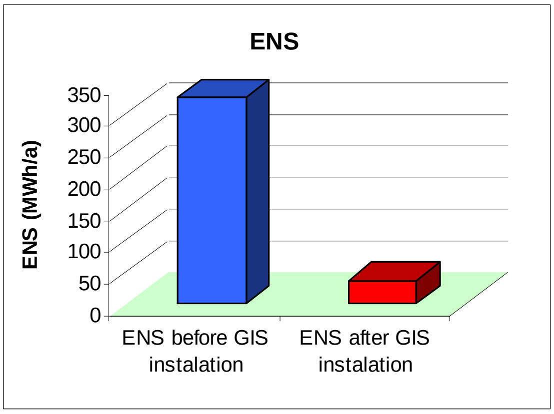

Fig. 11 ENS before and after GIS installation

6 Conclusion

Results of reliability assessments simulation of southern Croatian transmission network are presented in this paper. Two cases are simulated: before and after installation of GIS substation. Simulation results show significant improvement of reliability indices which makes investment in new GIS substation justified and reasonable. One of the reasons for such an improvement of reliability indices is application of GIS technology which is more reliable than classical solutions. Additional reason is change in network topology due to construction of new substation with related new overhead lines and cables.

7 References

[1] J. Endrenyi, Reliability Modeling in Electric Power Systems, Toronto, 1980.

[2] S. Nikolovski, P. Marić, D. Šljivac, I. Mravak, G. Slipac, Z. Kovač „Reliability Assessment od Croatian Power System After reconnection of UCTE1 and UCTE2 Synchronous Zone“ Conference proceedings, CIGRE 2006 General Session, Paris, France, August 2006, C1-301.

[3] DIgSILENT PowerFactory 14, User Manual, Gomaringen 2009

[4] Croatian Electric Utility HEP, Transmission System Operator. *Operational Events Statistics*, 2000 – 2007

[5] J. Nahman, V. Mihaljević, High Voltage Substations, Belgrade, 2000

[6] T.M. Chan, F. Heil, D. Kopejkova, Report on the Second International Survey on High Voltage Gas Isolated Substation (GIS) Service Experience, CIGRE, Paris Working Group 23. 20.1998, 23-102